NUWC-NPT Technical Memo 12-052

Generic Battery Rate-Effect Model

Mark E. Fuller
Autonomous and Defensive Systems Department

1 August 2012

NEWPORT

Naval Undersea Warfare Center Division
Newport, Rhode Island

ABSTRACT

This document presents a model for estimating battery performance as a function of the power level demanded. General values or data specific to a particular battery may be used to generate the required parameters for the model. All required information may be obtained from a typical vendor data sheet that includes constant-current discharge profiles. The total model is constructed of three separate components: (1) a model of cell open-circuit voltage as a function of battery state-of-charge, (2) capacity de-rating for constant-current discharge per Peukert's equation, and (3) application of Peukert's equation to variable current discharge.

ADMINISTRATIVE INFORMATION

This document was prepared under NUWC Division Newport Project No. 03307, "UUV Energy Sizing Model," principal investigator Benjamin Martin (Code 8231). The sponsoring activity is the Office of Naval Research (ONR-333).

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1. INTRODUCTION

As an alternative to the now-common method of battery system modeling by estimating overall values of specific energy and specific power on gravimetric and volumetric bases, independent of the rate of discharge, the model presented here is recommended for estimating battery performance as a function of the power level demanded. General values or data specific to a particular battery may be used to generate the required parameters for the model, shown in table 1. All required information may be obtained from a typical vendor data sheet that includes constant-current discharge profiles. Additionally, development of the model requires the variables in table 2. The total model is constructed of three separate components:

- a model of cell open-circuit voltage as a function of battery state-of-charge,[1]
- capacity de-rating for constant-current discharge per Peukert's equation,[2] and
- application of Peukert's equation to variable current discharge.[3]

Table 1. Battery Model Input Parameters

Symbol	Battery Parameter
E_{FULL}	Fully-charged potential
E_{EXP}	Potential at end of exponential zone
E_{NOM}	Potential at end of nominal zone
E_{CUT}	Cutoff potential
I_0	Specified/measured discharge current
m	Mass
pe	Peukert effect exponent
Q_{EXP}	Capacity discharged at end of exponential zone
Q_{NOM}	Capacity discharged at end of nominal zone
Q_{CUT}	Capacity discharged at cutoff
R_C	Internal resistance
v	Volume

Table 2. Additional Variables

Symbol	Variable
C	Capacity discharged
E_{OC}	Open-circuit potential
ED	Energy density (volumetric basis)
ES	Specific energy (gravimetric basis)
I	Actual discharge current
P	Discharge power
t	Time
τ	Total discharge time

2. EFFECT OF DISCHARGE CURRENT ON EFFECTIVE CAPACITY

2.1 PEUKERT'S EQUATION

In his study of lead-acid batteries, Peukert[2] observed a decrease in the available capacity of the battery with increasing discharge current, which could be modeled as

$$I^{pe} \cdot t = \text{constant},$$

where I is the discharge current, t is the time of discharge, and pe is a coefficient ("Peukert effect exponent") greater than one. Rearranging Peukert's law in terms of capacity C, Peukert's equation may be written to express the capacity (C_1) for a particular discharge current (I_1) as a function of a known current and capacity pairing (such as the nominal values frequently reported for commercial batteries, designated here as I_0 and C_0):

$$C_1 = C_0 \cdot \left(\frac{I_0}{I_1}\right)^{pe-1}. \tag{1}$$

The value of pe is empirically determined from experimental discharge data.

2.2 APPLICATION OF PEUKERT'S EQUATION

To model systems where the requirement is a constant delivered power, not a constant current discharge, equation (1) must be written in such a way as to allow computation of C_1 from a variable I_1. If time t is allowed to be an independent variable against which the various battery parameters may be tracked (i.e., the battery capacity C_1 is discharged at a rate of I_1 in time t_1), then

$$\frac{C_1}{C_0} = \left(\frac{I_0}{I_1}\right)^{pe-1} = \frac{I_1 \cdot t_1}{I_0 \cdot t_0} \equiv \frac{I_1 \cdot t_1}{I_{Effective} \cdot t_1},$$

$$I_{Effective} = I_1 \cdot \left(\frac{I_1}{I_0}\right)^{pe-1}, \tag{2}$$

$$C_{Effective} = \sum\left(I_{Effective} \cdot \Delta t\right). \tag{3}$$

The total capacity that may be discharged, per equation (3), may be set equal to the nominal capacity of the battery for determination of the available capacity during a variable-current discharge.[3]

3. OPEN-CIRCUIT POTENTIAL AS A FUNCTION OF STATE-OF-CHARGE

A simple model for determining battery open-circuit potential from the state of charge was developed in Tremblay et al.[1] This model is meant to simulate a battery as it is charged and discharged; i.e., it is applicable to secondary battery systems. The model specifically omits voltage recovery (an increase in voltage independent of the state-of-charge) and assumes the following:

- constant internal resistance,
- discharge characteristics of the battery represent the reverse of charge (reversible process),
- no effect of current on capacity (no Peukert effect),
- no temperature effects,
- no self-discharge,
- no memory effects.

The model, as presented by Tremblay et al., is

$$E_{OC} = E_0 - \left(\frac{K \cdot Q_{CUT}}{Q_{CUT} - C}\right) + (A \cdot \exp(-B \cdot C)) \,, \tag{4}$$

where

$$A \equiv E_{FULL} - E_{EXP} \,,$$

$$B \equiv \frac{3}{Q_{EXP}} \,,$$

$$K = \frac{(E_{FULL} - E_{NOM} + A(\exp(-B \cdot Q_{NOM}) - 1)) \cdot (Q_{CUT} - Q_{NOM})}{Q_{NOM}} \,,$$

$$E_0 = E_{FULL} + K + (R_C \cdot I_0) - A \,.$$

The model parameters are found from published manufacturer data and by inspection of constant-current discharge curves. Determination of the several values of E and Q from a discharge curve may be made according to figure 1. E_{FULL} (and Q_{FULL}, which is by definition zero) would be read from the point labeled "Fully charged voltage." Similarly, E_{EXP} and Q_{EXP} would be read from "End of exponential zone," E_{NOM} and Q_{NOM} would be read from "End of nominal zone," and E_{CUT} and Q_{CUT} would be read from the end of the curve. In the case of an abscissa marked in time and not capacity, as in figure 1, determination of the values of Q is the product of the value of the discharge current and the time indicated at each point. Additional details may be found in Tremblay et al.[1]

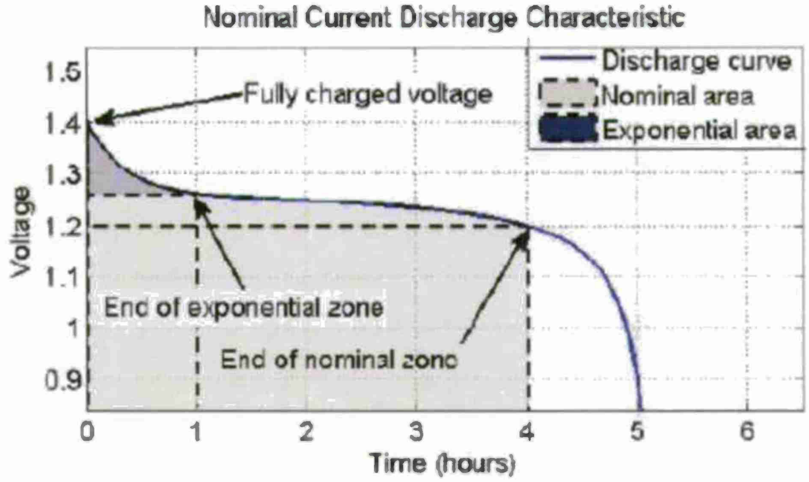


Figure 1. Identification of Discharge Profile Characteristic Values[1]

The model was validated against discharge curves for an individual Panasonic cell of each of the following chemistries (all secondary cells):

- lead-acid,
- nickel-cadmium,
- lithium, and
- nickel-metal hydride.

The authors of the above model presented a revised version of equation (4) in Tremblay and Dessaint,[4] including equations tailored specifically to each of the four secondary cell chemistries. The fine degree of increased accuracy provided by this improved model is insufficient to outweigh the costs of sacrificing a general equation of cell voltage for chemistry-specific formats; consequently, this revised model has been disregarded here.

4. A CONSTANT-POWER, CONSTANT-TEMPERATURE DISCHARGE MODEL

4.1 ORDINARY DIFFERENTIAL EQUATION FOR CAPACITY

While many battery cells may demonstrate nearly full capacity discharge at currents near the published or nominal rates, it is desirable to make theoretical predictions of battery behavior when systems are stressed. Integration of a capacity de-rating model[2,3] into a model for potential makes possible a more conservative evaluation of cell discharge at increased currents. Further, the model may be rearranged to define a constant-power state:

$$\frac{d(C_{Effective})}{dt} = \left[\frac{b - \sqrt{b^2 - 4 \cdot a \cdot P}}{2 \cdot a}\right]^{pe}, \tag{5}$$

where

$$a \equiv R_C \cdot \left(I_0^{\frac{2(pe-1)}{pe}} \right),$$

$$b \equiv \left[E_0 - \left(\frac{K \cdot Q_{CUT}}{Q_{CUT} - C_{Effective}} \right) + \left(A \cdot \exp(-B \cdot C_{Effective}) \right) \right] \cdot \left(I_0^{\frac{(pe-1)}{pe}} \right),$$

$$C_{Effective|t=0} \equiv 0.$$

The derivation of equation (5) is given in appendix A.

4.2 APPLICATION TO SIZING ESTIMATIONS

Integration from zero time until $C_{Effective}$ is equal to Q_{CUT} allows determination of the run time of the battery at the chosen power level:

$$C_{Effective|t=\tau} = Q_{CUT}.$$

For sizing purposes, the battery's specific energy and energy density may be determined from integration of equation (5):

$$ES = \frac{P \cdot \tau}{m}, \quad ED = \frac{P \cdot \tau}{v}. \tag{6}$$

Through inclusion in a computer program, sizing simulations may be carried out to determine available energy for the particular power level demanded, rather than relying on a more approximate value. An additional benefit of modeling battery behavior in this way is the handicapping of maximum power. The use of constant values for energy content requires a similarly crude estimation of maximum power output for a battery system, i.e., values for the battery's specific energy, specific power, and energy density. For the model presented here, the maximum power is automatically limited to

$$P_{Maximum} = \frac{(E_{FULL})^2}{4 \cdot R_c}. \tag{7}$$

The derivation of equation (7) is given in appendix B.

Appendix C presents an example to demonstrate the process by which this model might be used to predict battery performance.

REFERENCES

1. Oliver Tremblay, Louis-A. Dessaint, and Abdel Illah Dekkiche, "A Generic Battery Model for the Dynamic Simulation of Hybrid Electric Vehicles," IEEE 0-7803-9761-4/07, 2007.

2. W. Peukert, "Über die Abhängigkeit der Kapacität von der Entladestromstärke bei Bleiakkumulatoren," *Elektrotechnische Zeitschrift*, vol. 20, pp. 20-21, 1897.

3. D. Doerfel and S. Sharkh, "A Critical Review of the Peukert Equation for Determining the Remaining Capacity of Lead-Acid and Lithium-Ion Batteries," *Journal of Power Sources*, vol. 155, pp. 395-400, 2006.

4. O. Tremblay and L-A. Dessaint, "Experimental Validation of a Battery Dynamic Model for EV Applications, *World Electric Journal*, vol. 3, 2009.

APPENDIX A
DERIVATION OF EQUATION (5)

The voltage across the terminals of a battery is equivalent to the open-circuit voltage of the cell, less the voltage drop as calculated by Ohm's law:

$$E = E_{OC} - (R_C \cdot I)\,. \tag{A-1}$$

Drawing on the model developed in Tremblay et al.,[1] we may compute the open-circuit potential as a function of the state-of-charge as in equation (4). Substituting (4) into (A-1) and applying equation (2) yields

$$I = \left(I_{Effective}\left(I_0^{pe-1}\right)\right)^{\frac{1}{pe}},$$

$$E = E_0 - \left(\frac{K \cdot Q_{CUT}}{Q_{CUT} - C}\right) + (A \cdot \exp(-B \cdot C)) - \left[R_C \cdot \left(I_{Effective}\left(I_0^{pe-1}\right)\right)^{\frac{1}{pe}}\right]. \tag{A-2}$$

Also, as the original model presented in Tremblay et al.[1] is for a constant-capacity system with no Peukert effect, the tracked capacity in equation (A-2) should be the effective capacity. The effective capacity discharged at a particular current (equation (3)), evaluated for a current that is a function of time, may be written alternatively as an integral:

$$C_{Effective} = \sum\left(I_{Effective} \cdot \Delta t\right) = \int I_{Effective}\{t\}dt\,.$$

If the current function is assumed to be smooth, then it may be rewritten as the derivative of capacity discharged with respect to time:

$$\frac{d(C_{Effective})}{dt} = I_{Effective}\{t\}\,. \tag{A-3}$$

Removing references to current and replacing them with capacity, we obtain a final expression for potential:

$$E = E_0 - \left(\frac{K \cdot Q_{CUT}}{Q_{CUT} - C_{Effective}}\right) + \left(A \cdot \exp\left(-B \cdot C_{Effective}\right)\right) - \left[R_C \cdot \left(\frac{d(C_{Effective})}{dt}\left(I_0^{pe-1}\right)\right)^{\frac{1}{pe}}\right]. \tag{A-4}$$

For a constant-power system,

$$E_{OC} \equiv E_0 - \left(\frac{K \cdot Q_{CUT}}{Q_{CUT} - C}\right) + (A \cdot \exp(-B \cdot C))\,,$$

$$P = E \cdot I = \left[R_C \cdot E_{OC} - \left(\frac{d(C_{Effective})}{dt}\left(I_0^{pe-1}\right)\right)^{\frac{1}{pe}}\right] \cdot \left(\frac{d(C_{Effective})}{dt}\left(I_0^{pe-1}\right)\right)^{\frac{1}{pe}},$$

$$P = E_{OC} \cdot \left(\frac{d(C_{Effective})}{dt}\left(I_0^{pe-1}\right)\right)^{\frac{1}{pe}} - \left[R_C \cdot \left(\frac{d(C_{Effective})}{dt}\left(I_0^{pe-1}\right)\right)^{\frac{2}{pe}}\right],$$

$$a \cdot \left(\frac{d(C_{Effetive})}{dt}\right)^{\frac{2}{pe}} - b \cdot \left(\frac{d(C_{Effetive})}{dt}\right)^{\frac{1}{pe}} + P = 0\,, \qquad \text{(A-5)}$$

where

$$a \equiv R_C \cdot \left(I_0^{\frac{2(pe-1)}{pe}}\right),$$

$$b \equiv \left[E_0 - \left(\frac{K \cdot Q_{CUT}}{Q_{CUT} - C_{Effective}}\right) + \left(A \cdot \exp(-B \cdot C_{Effective})\right)\right] \cdot \left(I_0^{\frac{(pe-1)}{pe}}\right).$$

The derived function for a constant-power system (equation (A-5)) has the form of a quadratic equation, which may be solved for the value of the time-derivative of the effective capacity raised to the power of the reciprocal of the Peukert effect exponent. As a quadratic equation, there are two solutions: the positive and the negative radical in the numerator. By inspection, the physically correct solution to the differential equation is the negative of the radical so as to have zero current in the zero-power case.

In this form, the equation is an ordinary differential equation (ODE) and may be integrated to solve for the effective discharge against time, assuming an initial condition for battery discharge, e.g., that at the start ($t = 0$) the battery has not been discharged ($C_{Effective} = 0$). The result is equation (5):

$$\frac{d(C_{Effective})}{dt} = \left[\frac{b - \sqrt{b^2 - 4 \cdot a \cdot P}}{2 \cdot a}\right]^{pe},$$

$$C_{Effective|t=0} \equiv 0\,.$$

APPENDIX B
DERIVATION OF EQUATION (7)

The power delivered by a cell is equivalent to the product of the potential and current:

$$P = E \cdot I\,.$$

The cell potential may be written as the open-circuit potential less the ohmic loss due to internal resistance:

$$E = E_{OC} - I \cdot R_C\,.$$

The open-circuit voltage is maximized for a fully-charged cell at V_{FULL}, making the equation for power a function of two constants (open-circuit potential and cell resistance) and one variable (current):

$$P = I \cdot (E_{OC} - I \cdot R_C)\,,$$

$$P = E_{OC} \cdot I - R_C \cdot I^2. \tag{B-1}$$

Taking the derivative and setting to zero, we find the location of the maximum:

$$\frac{dP}{dI} = E_{OC} - 2 \cdot R_C \cdot I\,,$$

$$0 = E_{OC} - 2 \cdot R_C \cdot I\,,$$

$$I_{Maximum\ Power} = \frac{E_{OC}}{2 \cdot R_C}\,.$$

Substituting into equation (B-1), we determine the maximum power and we recover equation (7):

$$P_{Maximum} = E_{OC} \cdot \frac{E_{OC}}{2 \cdot R_C} - R_C \cdot \left(\frac{E_{OC}}{2 \cdot R_C}\right)^2 = \frac{(E_{FULL})^2}{4 \cdot R_C}\,.$$

APPENDIX C
APPLICATION OF MODEL TO AN ACTUAL BATTERY

To demonstrate the process by which this model might be used to predict battery performance, the following example is presented. To begin, a battery cell of interest is selected and its data sheet is analyzed to determine the parameters defined in table 1 in the main text. It is important to state that determination of the battery's parameters is a subjective and inexact process. The same data sheet may produce two slightly different sets of values when analyzed by two different engineers as this battery model is an idealization of the real discharge behavior of battery cells.

For this example, the chosen cell is the Saft Li-Ion VL 52 E cell (see data sheet at the end of this appendix). The values of the parameters for this cell are listed in table C-1.

Table C-1. Saft VL 52 E Model Parameters

Symbol	Battery Parameter
E_{FULL}	4.1 volts
E_{EXP}	3.9 volts
E_{NOM}	3.2 volts
E_{CUT}	2.5 volts
I_0	48.9 amperes
m	1.0 kg
pe	1.035
Q_{EXP}	2.5 A-hr
Q_{NOM}	45 A-hr
Q_{CUT}	48.9 A-hr
R_C	2e-3 ohms
v	0.48 liter

The mass and volume of the cell are explicitly defined in the data sheet as 1.0 kg and 0.48 liter, respectively. By inspection of the C-rate discharge curve* at 25°C on the back side of the data sheet, the value of E_{FULL} is 4.1 volts, E_{EXP} is 4.0 volts, E_{NOM} is 3.2 volts, and E_{CUT} is 2.5 volts. The corresponding capacities are approximately Q_{EXP} = 2.5 A-hr, Q_{NOM} = 45 A-hr, and Q_{CUT} = 48.9 A-hr. As the discharge is listed as the C-rate, the value of I_0 is equivalent to Q_{CUT}

*"C-rate" is an industry term for the current that will completely discharge the cell in 1 hour. Other discharge currents are expressed relative to this value; e.g., "C/10" is one-tenth of the C-rate, or the rate at which the cell should fully discharge in 10 hours, barring any effect of discharge rate on capacity. These values are, obviously, approximations.

Table C-2. Saft VL 52 E Discharge Rate and Capacity Calculated for pe = 1.035

Discharge Rate (C-Rate)	Data Sheet Capacity (A-hr)	Calculated Capacity (A-hr)
C	48.9	48.8
C/2	50.0	50.0
C/3	50.9	50.7
C/5	51.7	51.6
C/7	52.0	52.2
C/10	52.9	52.9

divided by 1 hour, 48.9 A. The value of the Peukert effect exponent is estimated by measuring the cell capacity against the discharge rate from the discharge curves on the data sheet. The values measured from the data sheet and the calculated values for the estimated Peukert effect exponent of 1.035 are shown in table C-2. Lastly, the value of the internal resistance of the cell R_C is estimated from the observed initial drop in the C-rate discharge curve. (In many cases a value of internal resistance is provided by the manufacturer and estimation is not required.) At zero discharged capacity, the cell voltage decreases from 4.1 to 4.0 volts. By Ohm's law, the difference in voltage is equal to the product of the current and the resistance, so $R_C \approx 0.1$ volt/ $I_0 \approx 0.002$ ohm.

To solve equation (5), a short program was written for MATLAB that employed the solver ODE45. To avoid integrating over an uncertain time interval, the ODE is inverted and integrated over the capacity interval of 0 to Q_{CUT}. Derivation of this format is as follows:

$$\frac{d(C_{Effective})}{dt} = \left[\frac{b - \sqrt{b^2 - 4 \cdot a \cdot P}}{2 \cdot a}\right]^{pe},$$

$$\frac{dt}{d(C_{Effective})} = \left[\frac{2 \cdot a}{b - \sqrt{b^2 - 4 \cdot a \cdot P}}\right]^{pe} = \left[\frac{2 \cdot a}{b - \sqrt{b^2 - 4 \cdot a \cdot P}} \cdot \frac{b + \sqrt{b^2 - 4 \cdot a \cdot P}}{b + \sqrt{b^2 - 4 \cdot a \cdot P}}\right]^{pe},$$

$$\frac{dt}{d(C_{Effective})} = \left[\frac{(2 \cdot a) \cdot (b + \sqrt{b^2 - 4 \cdot a \cdot P})}{b^2 - b^2 + 4 \cdot a \cdot P}\right]^{pe} = \left[\frac{b + \sqrt{b^2 - 4 \cdot a \cdot P}}{2 \cdot P}\right]^{pe},$$

$$\frac{dt}{d(C_{Effective})} = \left[\frac{b}{2 \cdot P} + \sqrt{\frac{b^2}{4 \cdot P^2} - \frac{a}{P}}\right]^{pe}. \qquad \text{(C-1)}$$

The time calculated as corresponding to the value of Q_{CUT} allows for the determination of the cell energy as a function of power. While this is a useful tool for estimating battery performance, a conservative approach requires imposing additional limits on the battery operation.

The cell used in this example—the Saft VL 52 E—has a stated maximum discharge current of 52 amperes, corresponding approximately to the 1-C rate. The published specific energy is also given as 185 W-h/kg. Figure C-1 plots the results of this model for the VL 52 E both with and without the power and energy limits on the cell specified by the manufacturer. Programatically, these bounds may be applied using a pair of "IF" statements; i.e. if the required power exceeds the limit, the energy is zero, and if the calculated energy exceeds the limit, it is reduced to the limiting value.

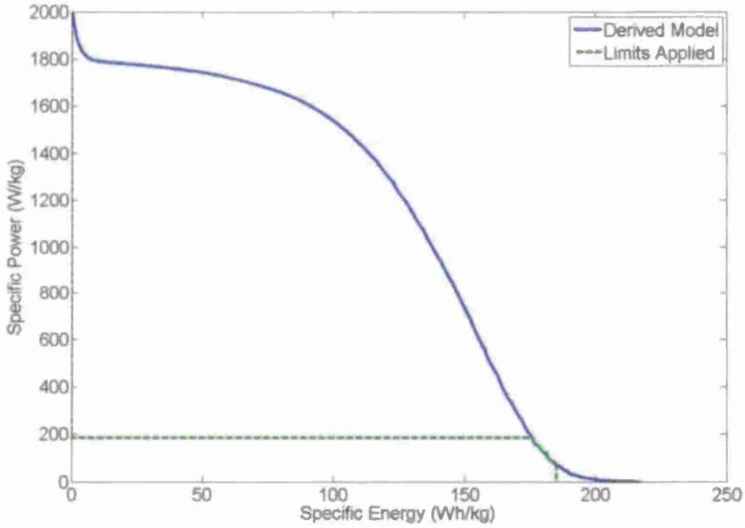


Figure C-1. VL 52 E Modeled Performance With and Without Manufacturer Limits

Rechargeable lithium-ion battery

VL 52 E - high energy cell

Benefits
- Excellent power density and specific energy
- 100% coulombic efficiency
- Low maintenance battery
- Long cycle life
- No memory effect

Typical applications
- High energy applications
- Defense
- Space

Key features
- Graphite-based anode
- Nickel alloy oxide-based cathode
- Sold only as assembled batteries
- Incorporation of electronics for performance efficiency:
  - Charge/floating/discharge management
  - Cell balancing

Battery level safety
- Incorporation of several levels of redundant safety features to prevent abuse conditions such as overcharge, over discharge and short circuit

Electrical characteristics		
Nominal voltage		3.6 V
Lower voltage limit for discharge		2.5 V
Maximum discharge current at RT continuous		52 Amps
Nominal capacity at 4.1 V/2.5 V and 25° C		52 (C/7) Ah
Specific energy*		185 Wh/Kg
Energy density*		385 Wh/l
Mechanical characteristics		
Nominal diameter		54 mm
Nominal height		208 mm
Nominal weight		1.0 kg
Nominal volume		0.48 l
Cell operating conditions		
Charge method		Constant current/constant voltage (CCCV)
Charging voltage		4.1 ± 0.04 V
Recommended continuous charge current at 25° C		C/7
Operating temperature:	Charge	+ 5° C to +35° C
	Discharge	- 25° C to + 55° C
Storage and transportation temperature		- 40° C to + 65° C
End of charge detection		150 mA
Total RT charging time		10 hours

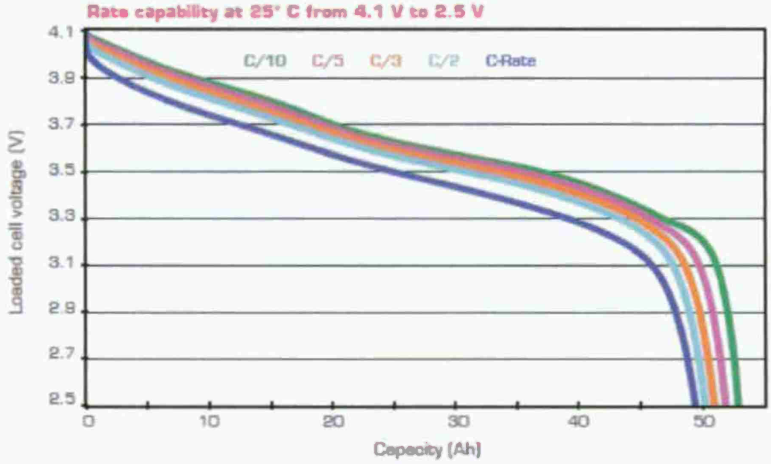
[1]Includes terminals
*Charge to 4.1 V and C/10 rate

August 2008

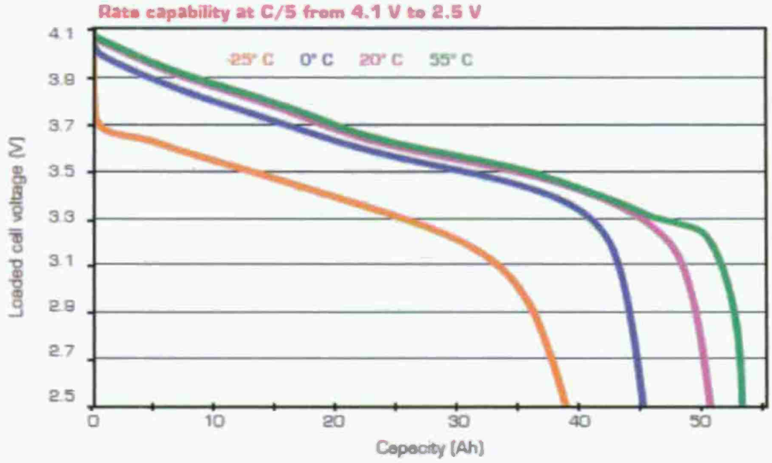
SAFT

VL 52 E

Rate capability at 25° C from 4.1 V to 2.5 V



Rate capability at C/5 from 4.1 V to 2.5 V



Saft America, Inc.
Space & Defense Division
107 Beaver Court
Cockeysville, MD 21030 - USA
Tel +1 410 771 3200
Fax +1 410 771 1144

www.saftbatteries.com

Doc N°: 54067-2-0808
Edition: August 2008

Data in this document are subject to change without notice and become contractual only after written confirmation by Saft.

Published by the Communications Department

Photo credit: Saft

Produced by Saft Space & Defense Division

saft

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE (*DD-MM-YYYY*)	2. REPORT TYPE	3. DATES COVERED (*From – To*)
01-08-2012		

4. TITLE AND SUBTITLE

Generic Battery Rate-Effect Model

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
0602747N

6. AUTHOR(S)

Mark E. Fuller

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Undersea Warfare Center Division
1176 Howell Street
Newport, RI 02841-1708

8. PERFORMING ORGANIZATION REPORT NUMBER

TM 12-052

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Research
One Liberty Plaza
875 North Randolph Street
Arlington, VA 22203-1995

10. SPONSORING/MONITOR'S ACRONYM

ONR

11. SPONSORING/MONITORING REPORT NUMBER

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This document presents a model for estimating battery performance as a function of the power level demanded. General values or data specific to a particular battery may be used to generate the required parameters for the model. All required information may be obtained from a typical vendor data sheet that includes constant-current discharge profiles. The total model is constructed of three separate components: (1) a model of cell open-circuit voltage as a function of battery state-of-charge, (2) capacity de-rating for constant-current discharge per Peukert's equation, and (3) application of Peukert's equation to variable current discharge.

15. SUBJECT TERMS

Battery Systems   Battery Performance   Battery Modeling   Battery Capacity   Peukert's Equation

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Mark E. Fuller
(U)	(U)	(U)	SAR	19	19b. TELEPHONE NUMBER (*Include area code*) 401-832-6262

DISTRIBUTION LIST

External

Office of Naval Research (ONR-333—M. Medeiros)
Defense Technical Information Center

Internal

Codes: 1144 (Technical Library)
82D (N. Dubois)
823 (J. Gomez)
823 (E. Dow)
8231 (J. Fontaine)
8231 (R. Roberts, A. Fredette, M. Fuller (2))
8233 (W. Krol)

Total: 12